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**LABORATORY 15 KV HIGH VOLTAGE
SOLAR ARRAY FACILITY**

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Lewis Research Center
Cleveland, Ohio
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16. Abstract <p>The laboratory high voltage solar array facility is a photoelectric power generating system. Consisting of nine modules with over 23 000 solar cells, the facility is capable of delivering more than a kilowatt of power. This paper describes the physical and electrical characteristics of the facility.</p>					
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SUMMARY

The laboratory high voltage solar array facility (HVSA) is a 15 kV (max.) photoelectric power generating system. The facility consists of nine identical modules each having a lamp bank and a panel of solar cells. The output voltage which may be obtained from a given module varies from 10 to approximately 1500 volts depending on internal wiring. Maximum power from a given module is in the neighborhood of 150 watts. Typically, modules exhibit small capacitances and essentially no inductance.

INTRODUCTION

The purpose of this paper is to provide a physical and electrical description of the NASA-Lewis Research Center laboratory high voltage solar array (HVSA) facility. The facility consists of nine modules, each of which contains a solar array and a lamp bank which is spectrally similar to the Sun. Each module can be configured from within to provide voltages over a range of 10 to approximately 1500 volts by changing the connections between strings of cells. The modules in turn may be put into any series - parallel configuration desirable by way of module to module interconnects or a patch panel to generate voltages up to approximately 13,500 volts. Each module can generate a maximum power of approximately 150 watts. A total power of up to 1350 watts may thus be extracted from the total facility.

The facility is primarily intended for experimental evaluation of the concept of integral regulation of high voltage solar arrays by electronically varying the number of active solar cells in series. This concept (which is discussed in refs. 1 to 3) eliminates the need for electronic power processing equipment with its attendant weight and power loss penalties. The facility may also be used as a source of solar electric power for evaluation of other power systems concepts (refs. 4 and 5).

This report presents electrical characteristics of the HVSA modules which were experimentally established with cells in each of the solar panels in series configuration. Static voltage current (V-I) curves were obtained and, from these, information about internal resistance and maximum power characteristics were derived. Module capacitance and inductance were measured with the arrays dark. Transient response data were obtained and from these data, a value of capacitance with arrays illuminated was derived.

FACILITY DESCRIPTION

General

The laboratory high voltage solar array facility consists of nine identical air and water cooler solar modules, associated power supplies, a centralized control console, a high voltage patch panel with metering, and wiring to either of two load areas.

Each of the nine modules contains a solar panel consisting of 2560 2- by 2-centimeter silicon solar cells which can be connected in a variety of series-parallel configurations providing a voltage range of 10 to approximately 1500 volts, a lamp bank of variable intensity, and an infrared filter mounted between the lamp bank and the solar panel. For these tests cells within the modules were configured in series providing an open circuit voltage in the neighborhood of 1450 volts. Air and water cooling are provided. Power to the lamps is controlled at a centralized control console.

High voltage outputs from the solar arrays are terminated on a patch panel where series - parallel configuring of the nine modules may be accomplished. These outputs are monitored by current and voltage meters at the patch panel. From the patch panel power may be taken to loads in one of two locations in the laboratory; a large vacuum facility (Tank 6) or a nearby smaller facility (Super Bell Jar 1). Figure 1 is a photograph of one of the modules opened to show the solar cell array and the lamp bank. Figure 2 is a photograph of the patch and meter panels. Figure 3 is a block diagram of the basic layout of the facility.

Control Console and Power Supplies

At the control console, the operator may control any module or combination of modules as required. Lamp intensity in each module may be individually adjusted at the console from zero to slightly greater than one Sun. Power supply output voltages are read on a digital panel meter mounted on the front of the control console. Additional features of the control console include audio and visual lampout failure and module over-temperature alarms as well as air and water temperature readouts. Nine 130 volt - 90 ampere d.c. power supplies are used to provide power to the lamps in the nine modules. These supplies are controlled at the centralized control console. Power supply protection is provided by a ramped voltage at turn-on in order to prevent large in-rush currents which might otherwise cause damage to the supplies. Full power is reached 20 seconds after turn-on of the supplies.

Modules

A typical module is essentially a box with a front and back door

which hinge down (fig. 4). The front door is an insulated, water cooled plate upon which the solar cells, on a Kapton substrate, are mounted. During operation, the substrate is held firmly against this plate by about 2.36×10^4 N/m² (7 in. Hg) of vacuum. The rear door is a lamp bank consisting of twenty 500 watt tungsten - iodide lamps. Measurements by the manufacturer (ref. 4) established the lamp bank illumination uniformity to be ± 5 percent over the solar array surface. This residual nonuniformity is compensated for by locating more efficient solar cells in the low illumination areas, which occur at the solar array borders. Mounted on each door are a resistance thermometer and a thermal switch which is part of the facility alarm system.

Between the front and rear door and dividing the module into two sections is an infrared filter. This filter serves the dual purpose of modifying the light IR spectrum incident upon the cells and forming a duct for the cooling air. Air is circulated down across the cells, through a semicircular plenum at the bottom of the module and up past the lamps by means of an exhaust fan. Reference 4 gives detailed information on the individual modules regarding solar cell layout and high voltage, light, thermal, mechanical, and control design features.

Patch Panels and Meters

High voltage outputs from the solar arrays are connected to a patch panel which was designed for a breakdown voltage of 30 000 volts. These outputs are terminated at points marked M-1, M-2, . . . , M-8 in figure 5. Heavy lines in this figure represent bundles of wires; regular lines represent individual wires. Series-parallel configuring of the modules may be accomplished here, as well as at the back of the modules. When desired series-parallel configuring is accomplished, the outputs are brought across to points 1, 2, 3, . . . , 12 on the right-hand side of the patch panel. At these points current and voltage are monitored (figs. 5 and 6) by meters mounted in a lucite box adjacent to the patch panel. This box is subsequently referred to as the meter panel. Points 1 to 12 also go to a set of normally closed relays (grounding relays). These relays are an integral element of system safety and are discussed in the section on Alarms and Safety.

From the patch panel the high voltage may be taken to loads either in Tank Number 6 or in Super Bell Jar Number 1.

Alarms and Safety

The laboratory high voltage array facility includes the following safety and alarm features:

- Audible lamp out and module over temperature alarms

- Module indicator lights
- Interlock system

In the event that a lamp should fail in any of the nine modules during operation a sensing circuit on the module triggers an audible alarm siren on the control console. A module indicator light also comes on to show the operator in which of the modules the failure has occurred. The facility may then be shut down and the fault corrected. The front and rear door of each module are equipped with temperature sensors which trigger the siren and indicator light in the event that an overtemperature failure occurs.

The entire facility is interlocked in such a manner that all power is automatically shut down in the event that:

- (1) A front or rear module door is opened
- (2) The patch panel or meter panel is opened

If either of the above actions occur during operation of the facility, power to the lamps is terminated and the relays in the patch panel ground the capacitively accumulated charge from the surface of the arrays. All interlock switches are in series with the power line to the control console. Additional interlocks may be added into this line if desired.

Care must be taken not to touch the cells when a module is open since room light is sufficient to generate a considerable voltage. A black plastic cover is normally placed over the cells when a module is open.

Water Flow Indicator and Temperature Readout

The front door of a module is an insulated, water cooled plate on which the solar array substrates are mounted. Water flows through a jacket on the outside surface of the door and maintains an average temperature of $\sim 16^{\circ}\text{C}$ (60°F). Water flow for each module is measured on an in-line flowmeter and is usually maintained at a value of 1.26×10^{-4} to $1.88 \times 10^{-4} \text{ M}^3/\text{sec}$ (2-3 gpm) during operation. A failure in water flow (due to blockage in the line for example) would result in a rise in solar cell temperature and, consequently, an alarm and/or a decrease in output voltage. These changes may be immediately detected by the facility operator who may then shut down and take proper corrective steps. A temperature readout system is also provided. Two selector switches on the control console permit the operator to select one of the nine modules and one of the four following temperatures:

- Air temperature at the top of the module
- Air temperature at the bottom of the module

- Water temperature
- Solar cell temperature

Temperatures are read on a digital panel meter mounted on the front of the control console calibrated to read in degrees Fahrenheit.

PERFORMANCE CHARACTERISTICS

Static V-I Curves

Static voltage against current (V-I) curves were obtained from all modules at a light intensity equivalent to one Sun and an average cold plate temperature of 54° F. In each module, all solar cells were wired in series. Array parameters were calculated then averaged for all modules. These averaged values are shown in table I. The following definitions apply to all tables:

V_{oc}	open circuit voltage
I_{sc}	short circuit current
P_m	maximum power
FF	fill factor ($P_m/V_{oc}I_{sc}$)
R_s	internal resistance at V_{oc}
R_{sh}	internal resistance at I_{sc}

Additional sets of V-I curves were obtained from a representative module (number 4). One set was taken at constant light intensity with temperature as a parameter. A second set was taken at constant temperature with light intensity as a parameter. In both cases I_{sc} is used as a measure of light intensity. Once a desired intensity is achieved, power supply voltage (V_{ps}) is held constant in order to maintain this intensity. The results of these two tests are tabulated in tables II and III. Copies of the V-I curves from which these data (tables I to III) were obtained are included at the end of this report as an appendix.

Capacitance and Inductance

With lamps off, inductance and capacitance bridge measurements were made of the solar array in module number 4. Connection of the bridges to the array were made at the patch panel so that measurements would include effects of the high voltage wiring from the array. Tests of the high voltage wiring alone (array shorted) were also conducted at the patch panel. The numerical data thus obtained is presented below.

Array capacitance (dark) ± 38 PF

Array inductance (dark) ± 0

Inductance of H.V. wiring ± 0
(Array shorted)

Transient Response

The circuit shown in figure 7 was used to obtain the transient current and voltage response of the solar array in module number 4. A vacuum triode was used to load the array. Variation of grid potential of the tube controlled the load on the solar array resulting in a change of voltage and current generated by the solar array. In order to determine the response of the solar array to a rapid change in load, a square wave signal was impressed upon the grid of the tube. Waveforms of array voltage and current were obtained at a number of different frequencies ranging from 10 Hz to 10 kHz.

A number of response curves are presented in figure 8. Rounding off of these waveforms at the higher frequencies is believed due to array capacitance. The frequency response of the tube alone was checked with a square wave and found to remain flat throughout the entire frequency range used in this test.

Evaluation of data given by the 6000 Hz curve yields a value of array capacitance of approximately 5×10^{-3} μ F. The analysis by which this value is obtained is given below.

By definition, current is given by the equation $I = \frac{dQ}{dt} = C \frac{dV}{dt}$. In order to eliminate error in estimating actual level of current from the oscillogram, the first derivative of I is used. Thus: $\frac{dI}{dt} = C \frac{d^2V}{dt^2}$. Or by way of approximation the time rate of change of current measured at time t_1 is:

$$\frac{\Delta I}{\Delta t} = C \frac{\left(\frac{\Delta V}{\Delta t} \Big|_{t_2} - \frac{\Delta V}{\Delta t} \Big|_{t_1} \right)}{t_2 - t_1}$$

where $\frac{\Delta V}{\Delta t} \Big|_{t_1}$ is the time rate of change of voltage measured at a specific time t_1 , similarly for $\frac{\Delta V}{\Delta t} \Big|_{t_2}$. From which we find the capacitance C :

$$C = \frac{\frac{\Delta I}{\Delta t}}{\left(\frac{\Delta V}{\Delta t} \Big|_{t_2} - \frac{\Delta V}{\Delta t} \Big|_{t_1} \right)} (t_2 - t_1)$$

$t_1 = 0$ is taken to be the point at which the current just starts to fall. t_2 is arbitrarily selected as a point in time 10 μsec after t_1 . Numerical calculations are as follows:

$$\frac{\Delta I}{\Delta t} = 0.002 \text{ A}/\mu\text{sec}$$

$$\frac{\Delta V}{\Delta t} \Big|_{t_1=0} = 9.600 \text{ V}/\mu\text{sec}$$

$$\frac{\Delta V}{\Delta t} \Big|_{t_2=10\mu\text{s}} = 5.333 \text{ V}/\mu\text{sec}$$

$$t_2 - t_1 = 10 \mu\text{sec}$$

$$C = \frac{0.002 \text{ A}/\mu\text{sec}}{9.600 \text{ V}/\mu\text{sec} - 5.333 \text{ V}/\mu\text{sec}} \times 10^{-5} \text{ S F}$$

$$C = 0.000469 \times 10^{-5} \text{ F}$$

$$= 4.69 \times 10^{-3} \mu\text{F}$$

An approximate value of $5 \times 10^{-3} \mu\text{F}$ is arrived at after rounding off the decimal. Similar calculations using oscillographs at different frequencies yield values of capacitance very close to the above stated value. This value is somewhat higher than that obtained with the arrays dark which is to be expected, due to the effects of solar cell diffusion capacitance.

CONCLUDING REMARKS

The laboratory high voltage solar array facility consisting of nine modules with over 23 000 solar cells is capable of generating over 1 kilowatt of d.c. power at any desired voltage from 10 volts to approximately 10 kilovolts. The facility was subjected to a number of tests in order to obtain typical physical and electrical parameters. Electrical output characteristics were measured at several solar array temperatures and illumination levels. The capacitance and inductance were measured both with and without illumination. The transient response of the array was also investigated. This characterization provides a good foundation for understanding and efficiently using the facility as a solar array power generating system and for proper evaluation of results obtained with it.

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2. Springgate, W. F.: High Voltage Solar Array Electrical Configuration Study. (D180-10037-1 Boeing Co.; NAS 3-8995), NASA CR-72723, 1970.
3. Herron, B. G.; et al.: High Voltage Solar Array Configuration Study. (Hughes Aircraft Co.; NAS 3-8996), NASA CR-72724, 1970.
4. Levy, E., Jr.; and Hoffman, A.C.: High Voltage Solar Cell Power Generating System for Regulated Solar Array Development. AIAA Paper 73-1105, Oct.-Nov. 1973.
5. Stover, J.: System Tests with Electric Thruster Beam and Accelerator Directly Powered from Laboratory Solar Arrays. NASA TM X-3353, 1975.

APPENDIX - TYPICAL VI CHARACTERISTIC CURVES

(MODULES 3 - 9)

TABLE I. - AVERAGED NUMERICAL DATA ON SOLAR

PANELS AT LIGHT INTENSITY OF 1 SUN AND

AVERAGE TEMPERATURE OF 54° F

R_s , K Ω	R_{sh} , K Ω	P_m , W	V_{oc} , V	I_{sc} , mA	FF, percent
1.08	241	147	1450	131	77

TABLE II. - NUMERICAL DATA ON MODULE NUMBER 4

WITH $V_{PS} = 1.27.1$ (1 SUN) AND TEMPERATURE

AS A PARAMETER

T, °F	R_s , K Ω	R_{sh} , K Ω	P_m , W	V_{oc} , V	I_{sc} , mA	FF, percent
70	1.46	87.1	130	1390	129	73
77	1.46	87.2	126	1366	129	72
85	1.46	63.3	122	1300	129	73
91	1.46	53.3	115	1250	129	72

TABLE III. - NUMERICAL DATA ON MODULE NUMBER 4 WITH

$T = 77^\circ$ F AND V_{PS} AS A PARAMETER

V_{PS} , V	R_s , K Ω	R_{sh} , K Ω	P_m , W	V_{oc} , V	I_{sc} , mA	FF, percent	Intensity, Suns
127.1	1.01	75	126	1360	137	68	1.00
120	1.14	84	110	1360	111	73	.81
110	1.31	106	88	1350	91	72	.66
100	1.43	98	70	1340	74	70	.54
90	1.77	115	52	1330	56	69	.41
80	2.18	159	37	1300	42	69	.31
70	3.60	230	24	1280	28	68	.20
60	6.44	259	14	1200	18	65	.13
40	39	404	2	1100	5	35	.04

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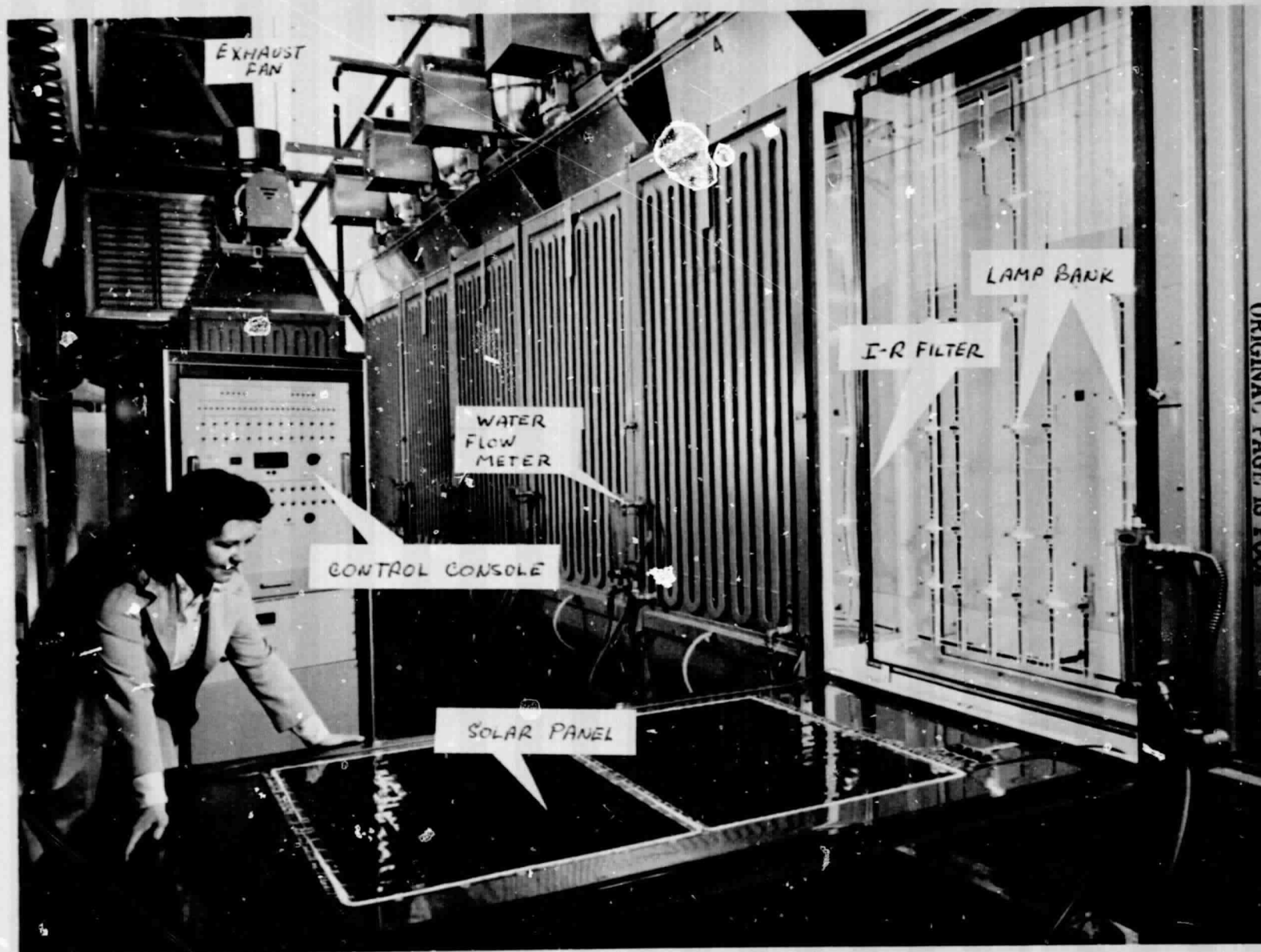


FIG. 1.
HVSA TEST AREA

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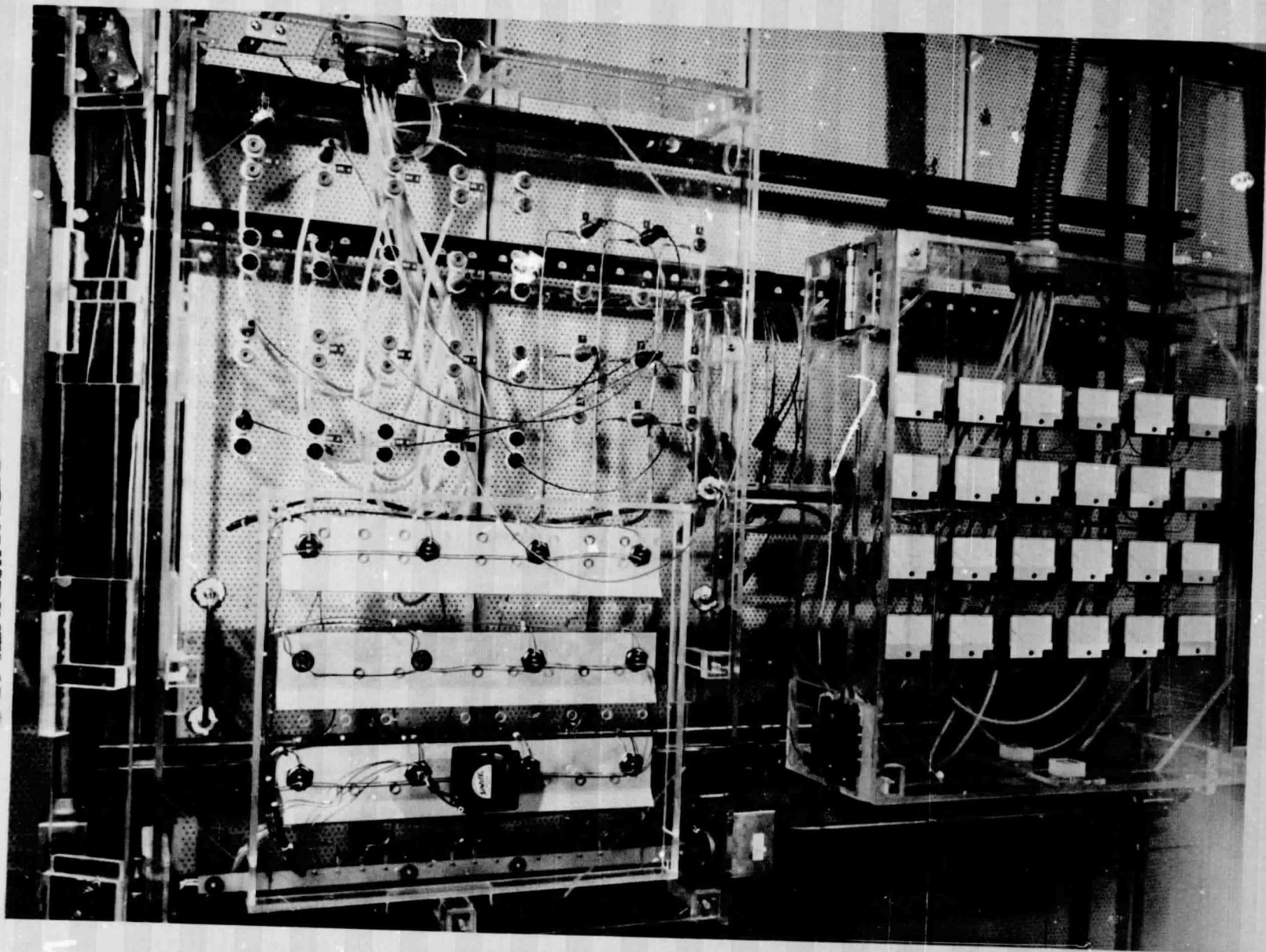


FIG. 2.
PATCH AND METER PANELS

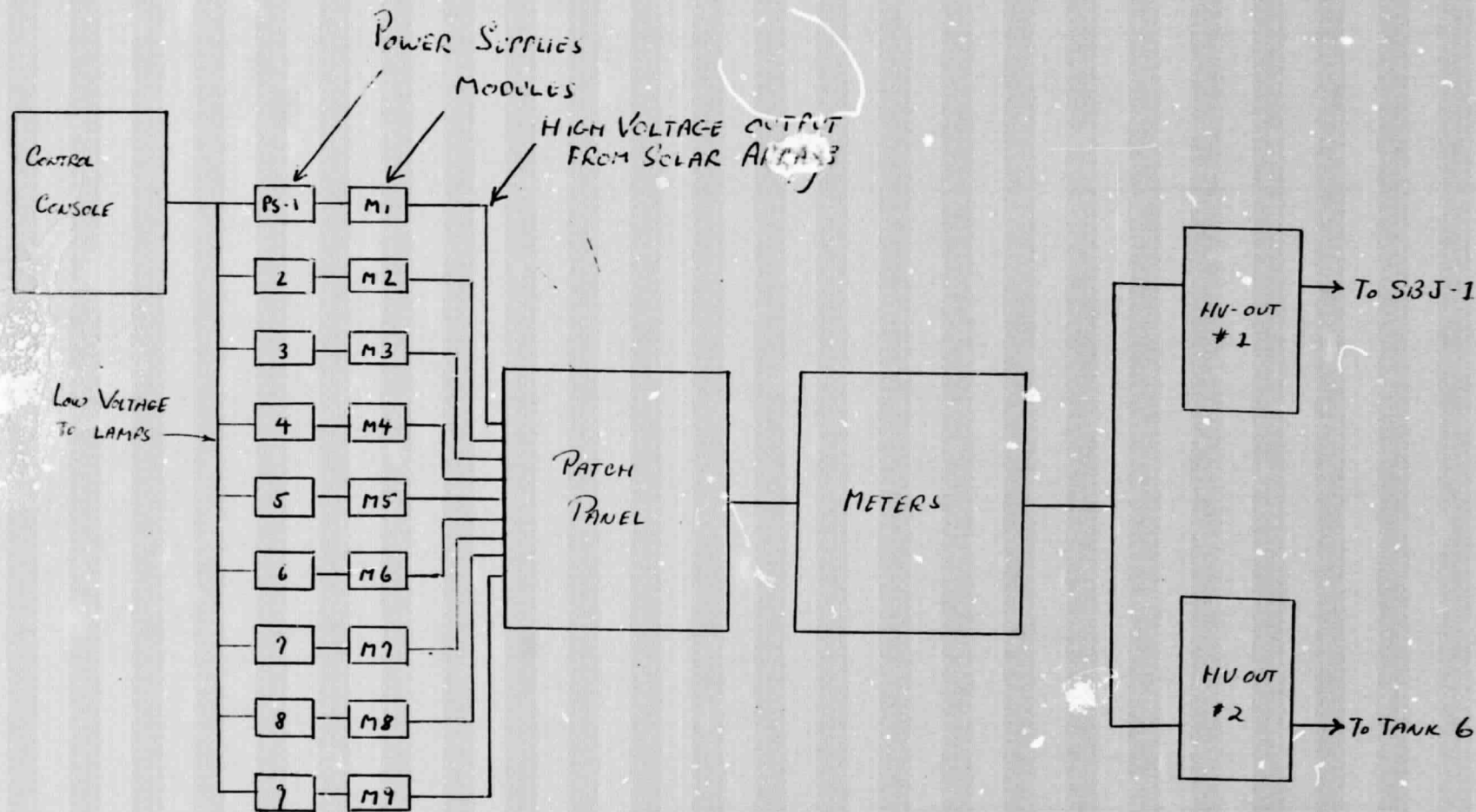


FIG. 1 BLOCK DIAGRAM OF IR/HUSA LAB CONFIGURATION

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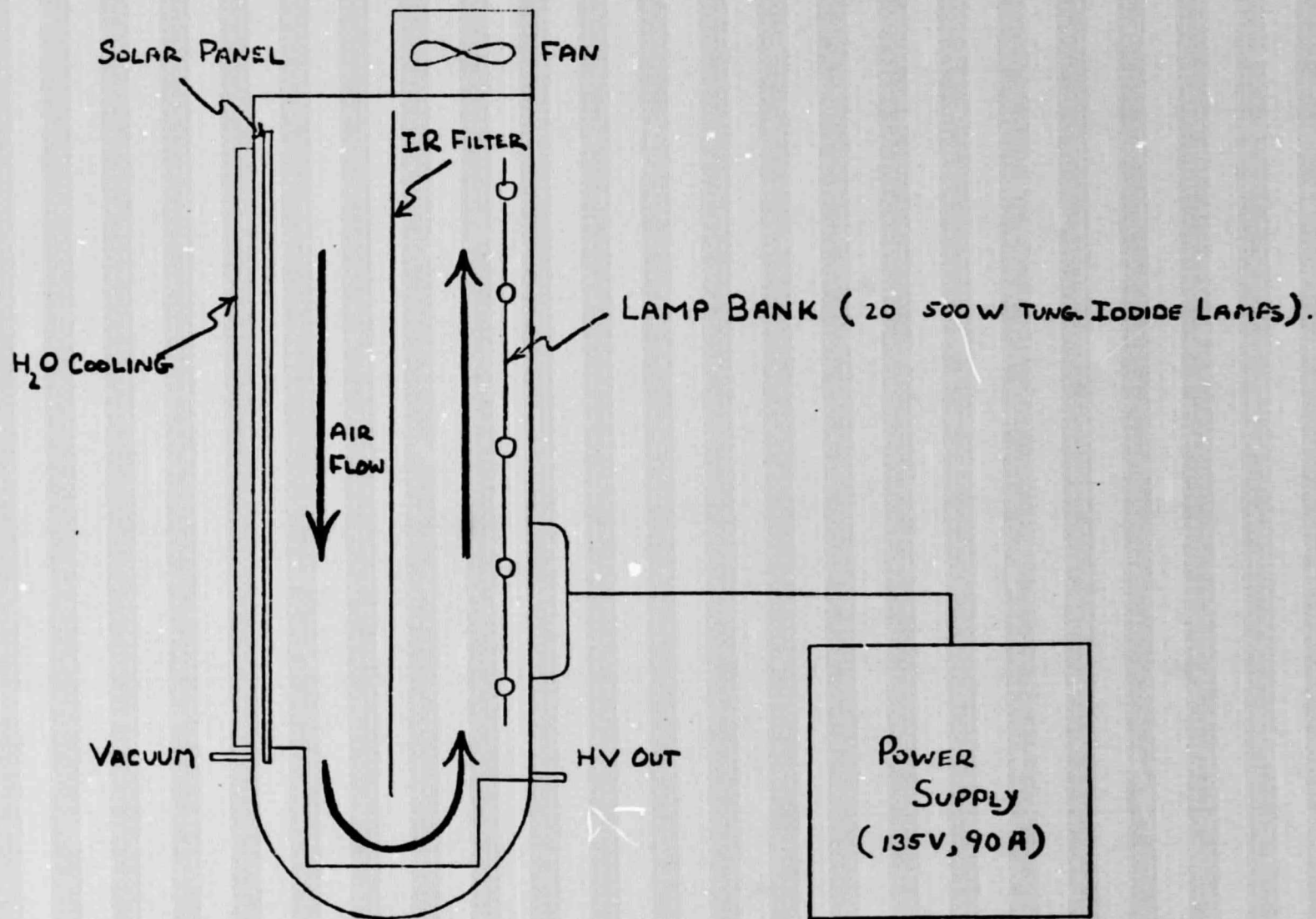
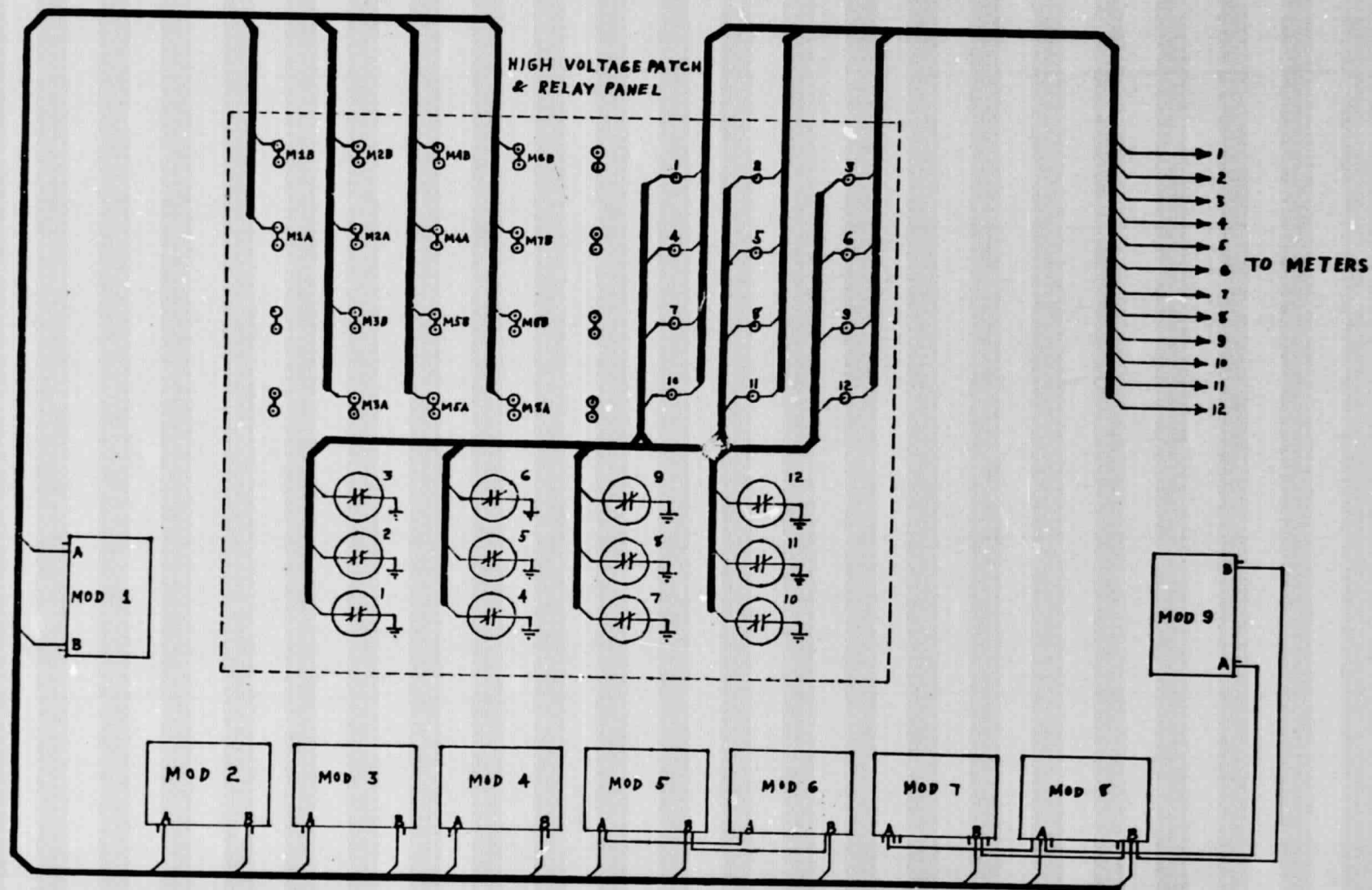


FIG. 4 TYPICAL MODULE

FIG. 5. HVSA - HIGH VOLTAGE WIRING



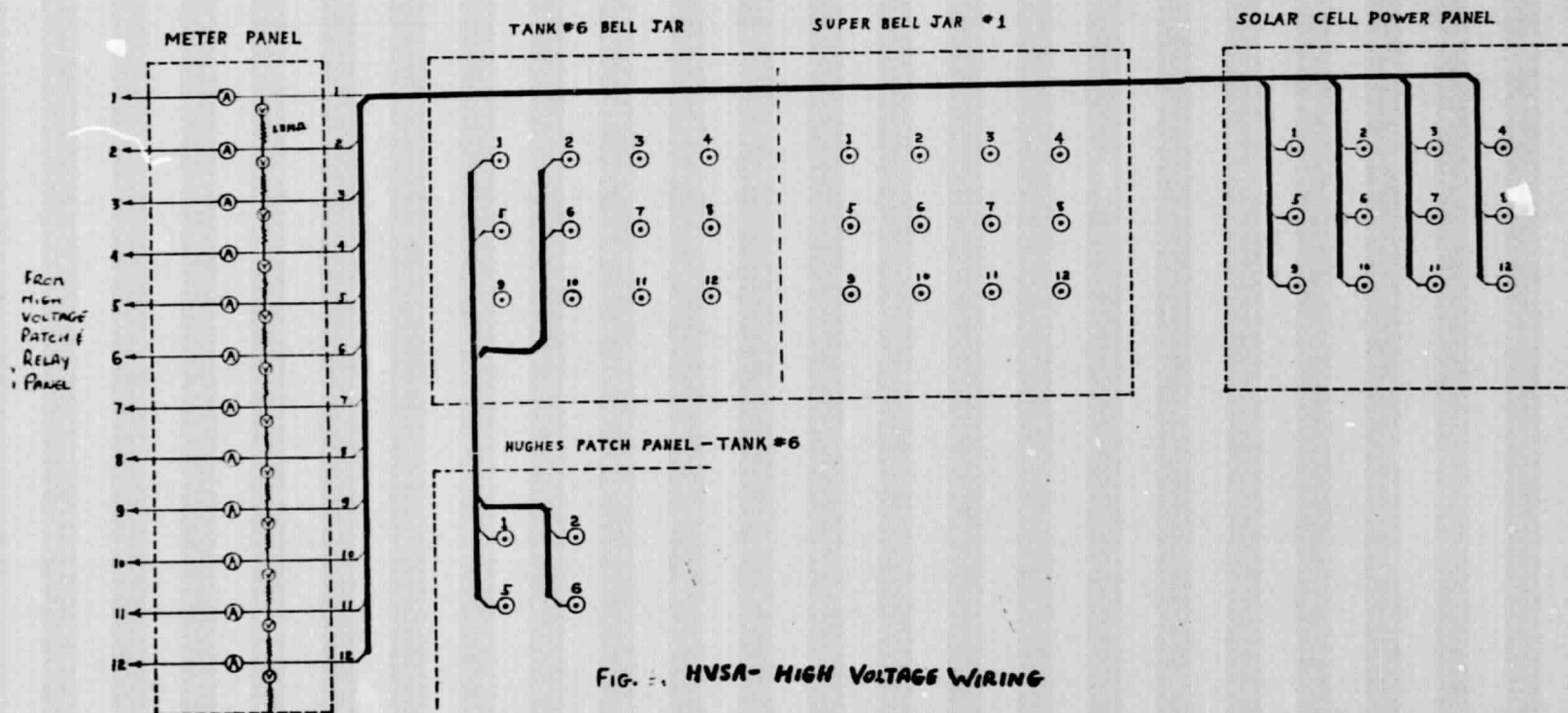


FIG. 1. HVSA- HIGH VOLTAGE WIRING

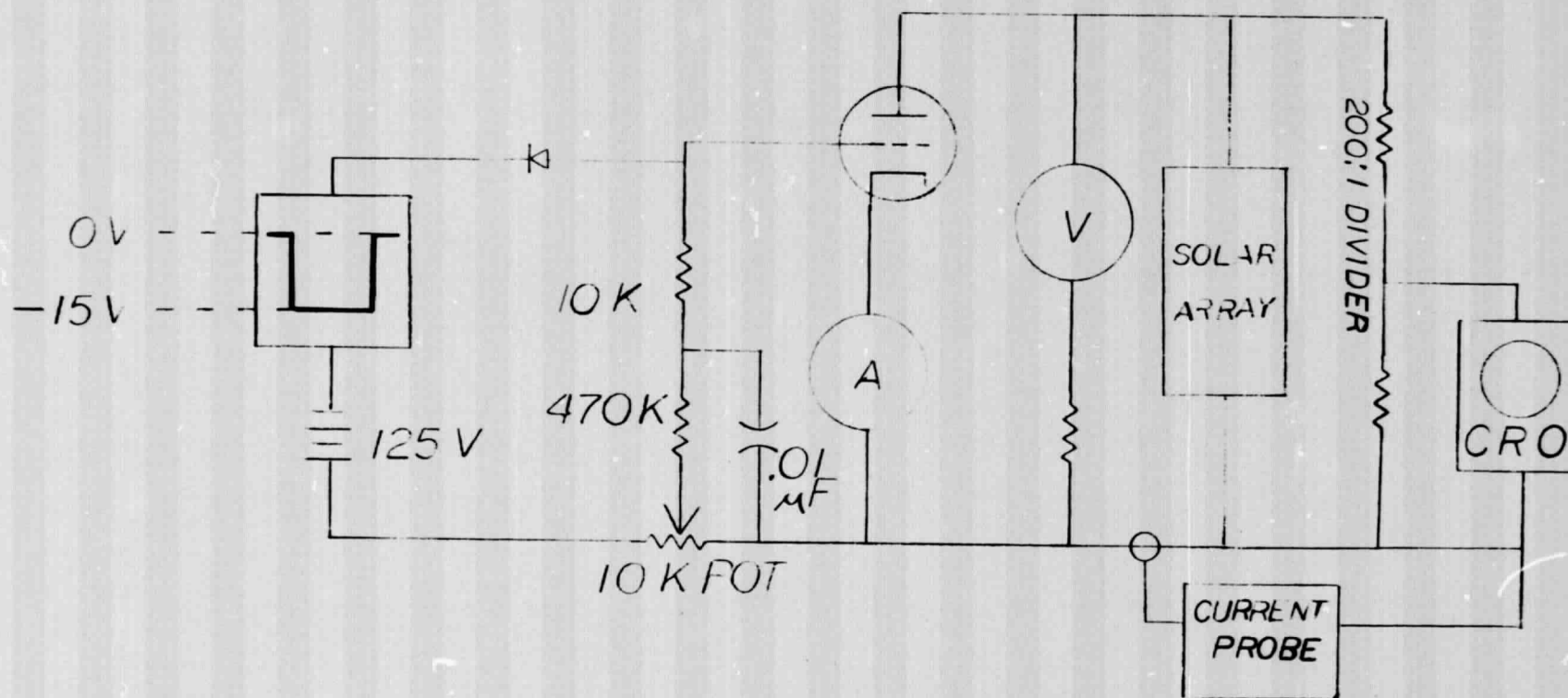
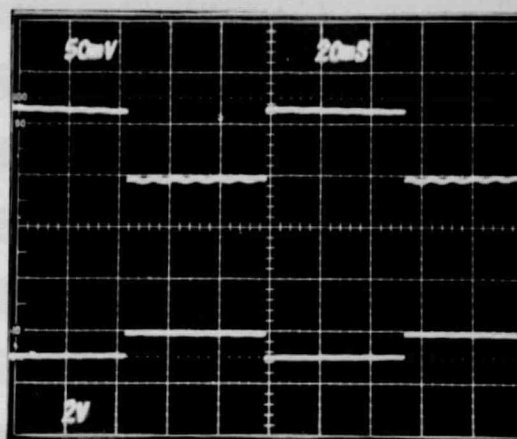
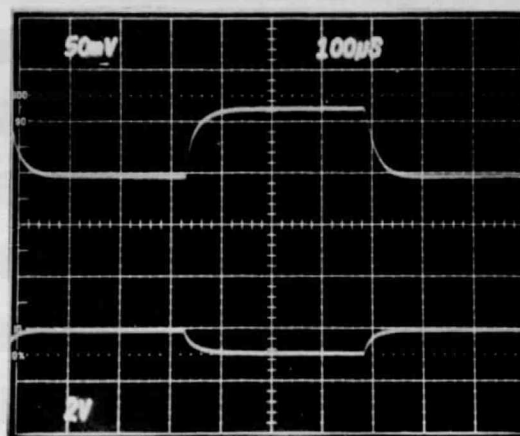


FIG 7 TEST CIRCUIT FOR TRANSIENT RESPONSE MEASUREMENT

FREQUENCY=10 HZ



1500 HZ



6000 HZ

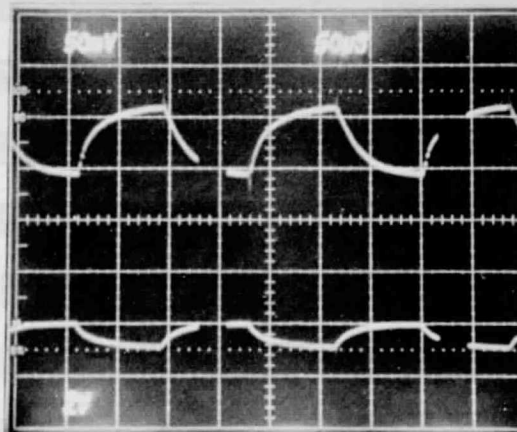


FIG. 8.

TRANSIENT
RESPONSE

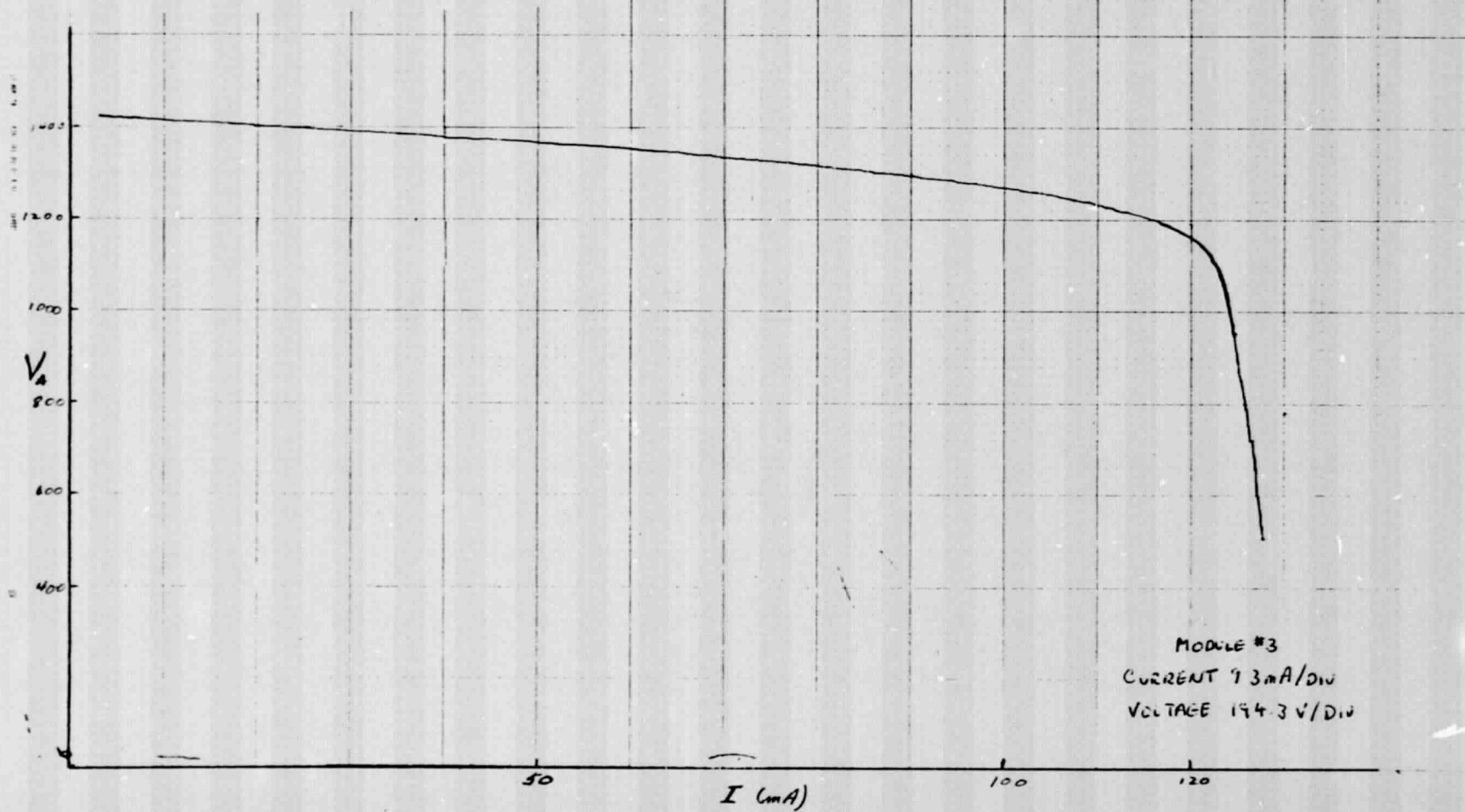
TOP 50 mA/DIV
BOTTOM 400 VOLTS/DIV

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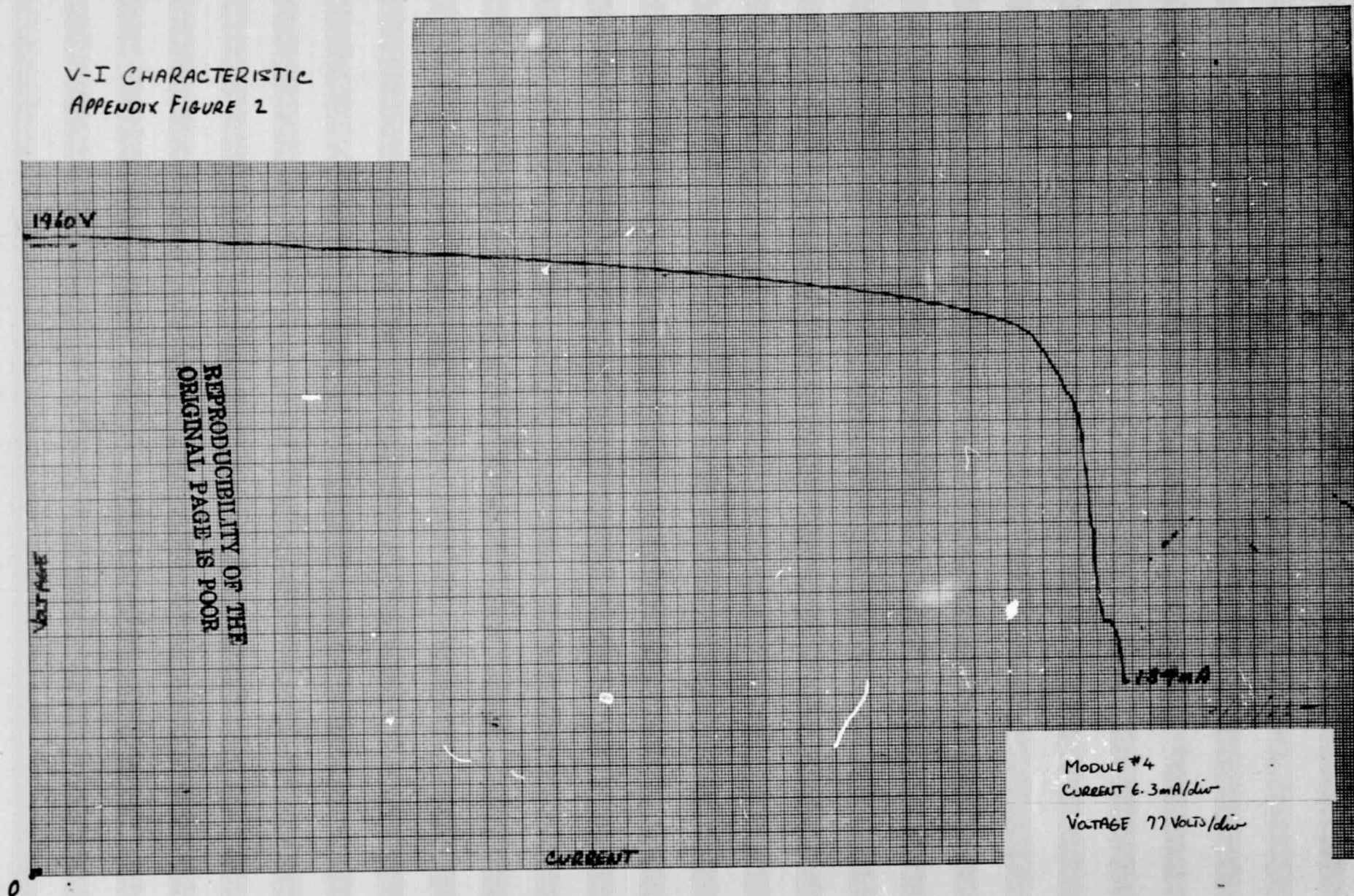
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M3

V-I CHARACTERISTIC APPENDIX FIGURE 1

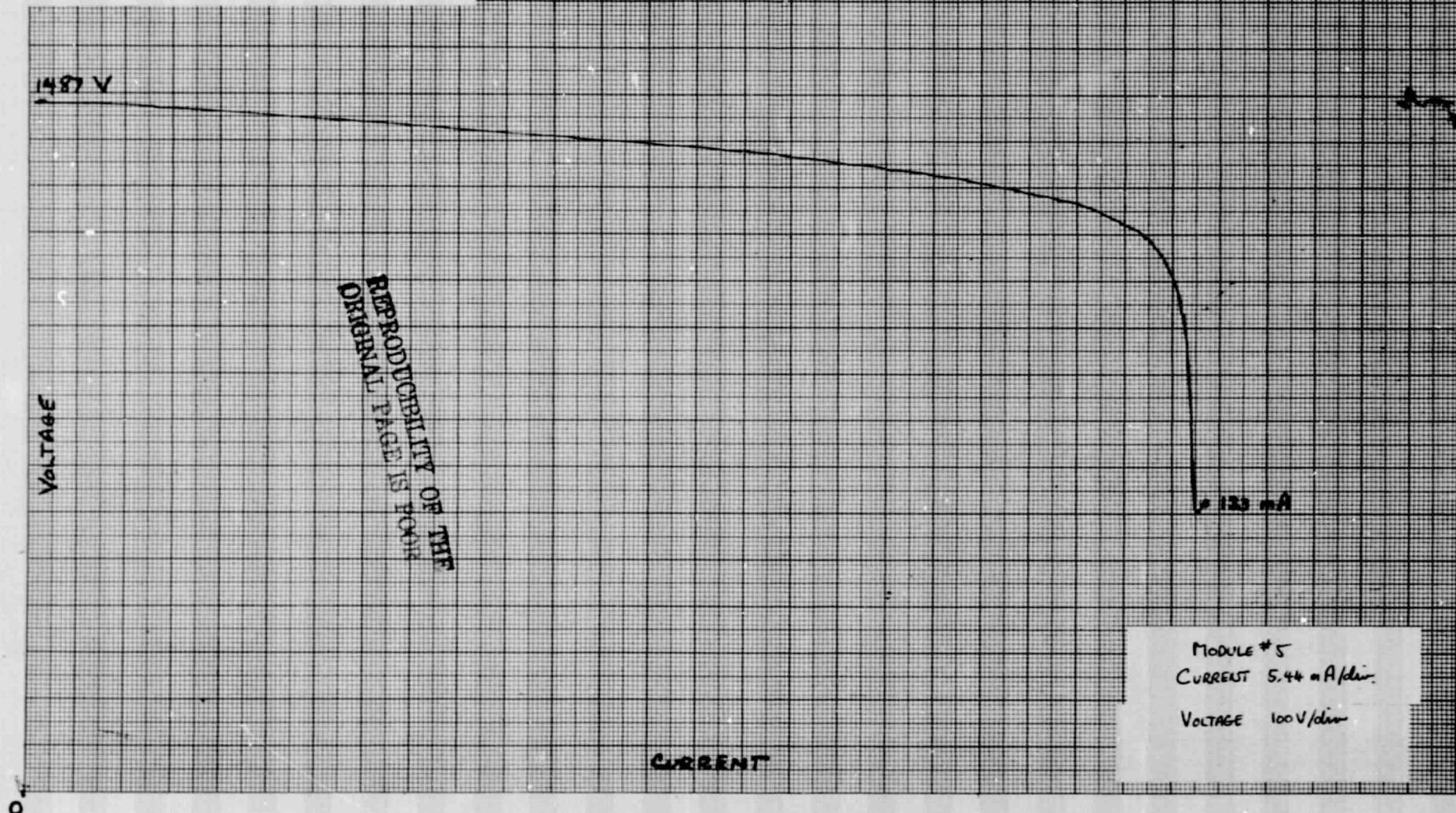


V-I CHARACTERISTIC
APPENDIX FIGURE 2

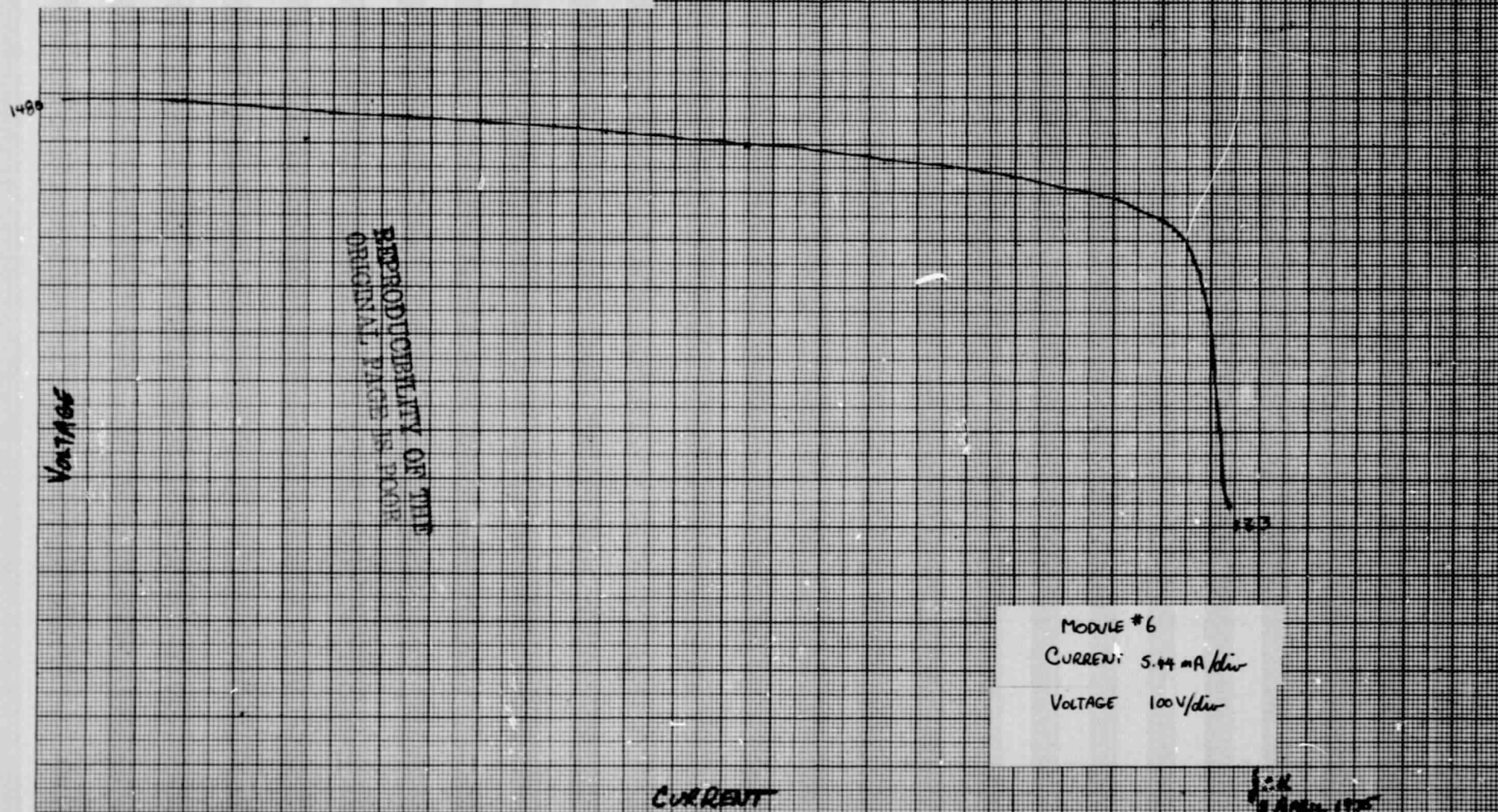


V-I CHARACTERISTIC

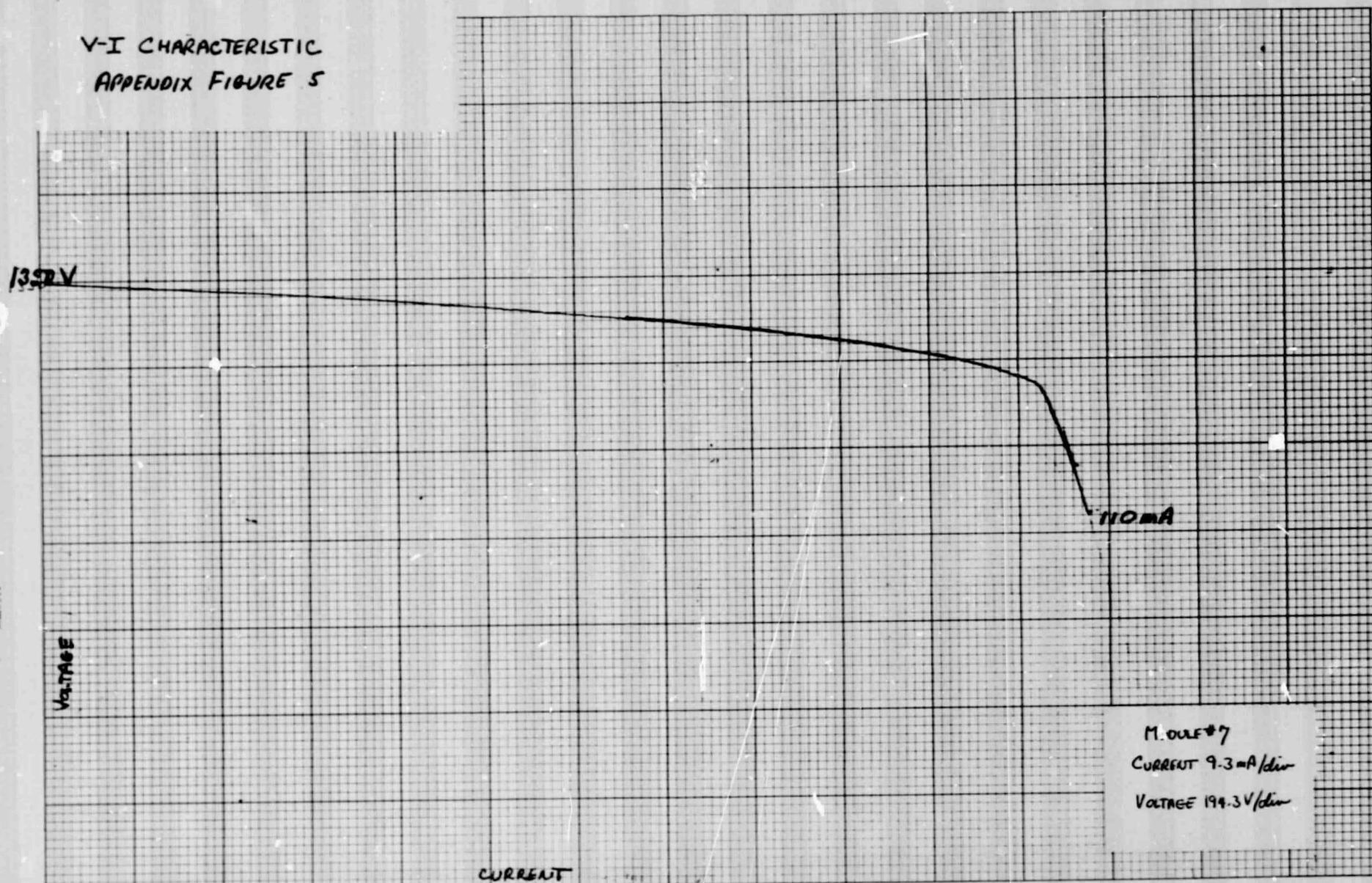
APPENDIX FIGURE 3



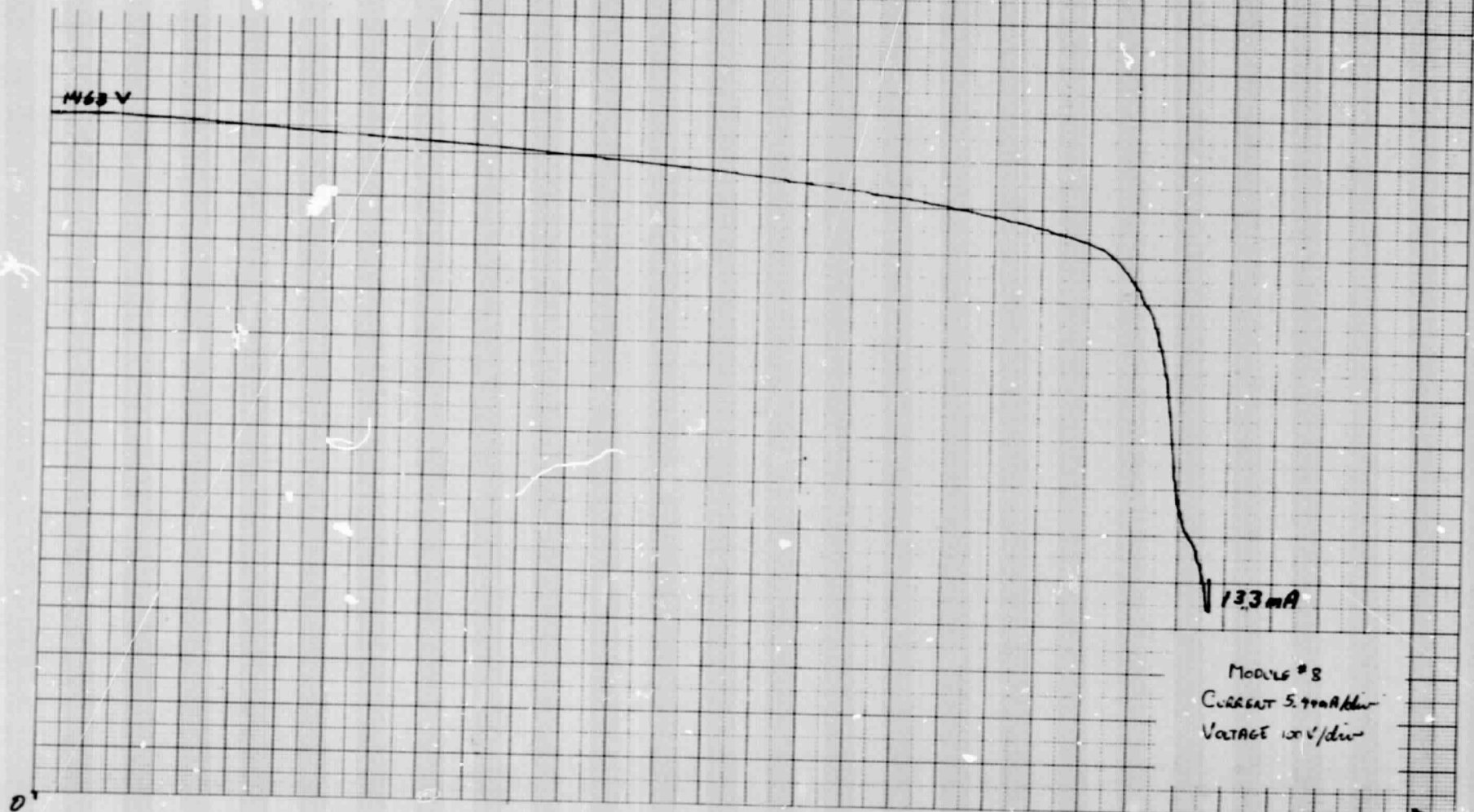
V-I CHARACTERISTIC
APPENDIX FIGURE 4



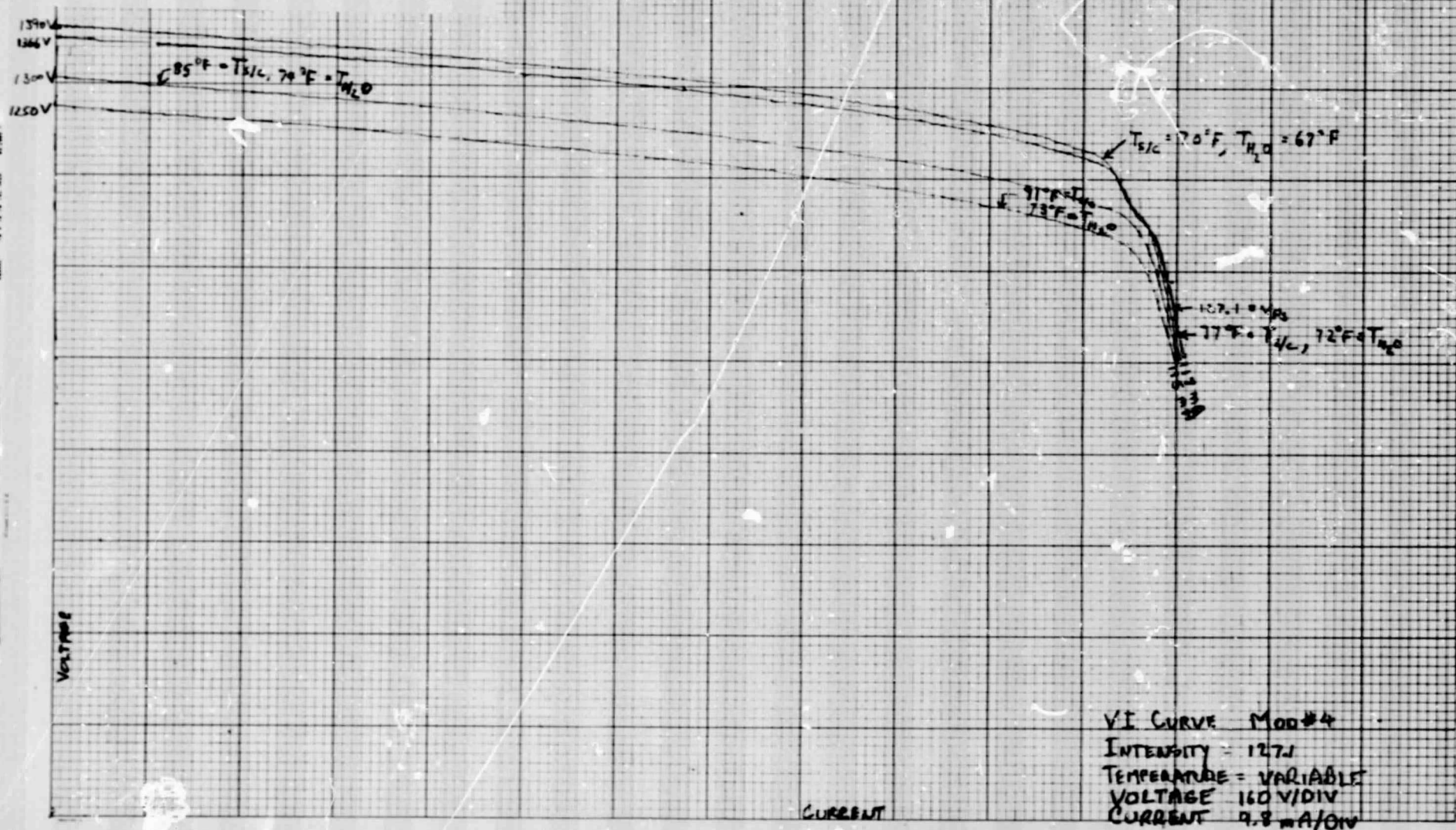
V-I CHARACTERISTIC
APPENDIX FIGURE 5



V-I CHARACTERISTIC
APPENDIX FIGURE 6



V-I CHARACTERISTICS
INTENSITY VARIATION EXPERIMENT
APPENDIX FIGURE 8



V-I CHARACTERISTICS TEMPERATURE VARIATION EXPERIMENT APPENDIX FIGURE 9

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